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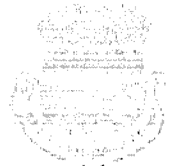
ARRAY CROSSED-FIELD

DEVELOPMENT



TECHNICAL REPORT NO. RADC-TR-68-122

[illegible] PHASED ARRAY CROSSED-FIELD

AMPLI[illegible] DEVELOPMENT

A. [illegible]

[illegible]-D Laboratories, Incorporated

TECHNICAL REPORT NO. [illegible]-TR-68-122

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C-BAND PHASED ARRAY CROSSED-FIELD AMPLIFIER DEVELOPMENT

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S-F-D Laboratories, Incorporated

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ABSTRACT

This program effort has two main objectives. The first objective is to demonstrate the feasibility of an RF turn-on, RF turn-off, reentrant stream crossed-field amplifier. The reliability of RF turn on has previously been demonstrated and during this reporting period the feasibility of reliable RF turn off has also been demonstrated at peak power levels up to 700 kw with a net gain of 10 db.

The second objective of this program is to increase the power output capability previously demonstrated under Contract AF30(602)-4082 by a factor of two. During this reporting period a circular cold test version of the anode slow wave circuit has been constructed and evaluated. The transition matches are being evaluated for their high power applications and construction of the first hot test vehicle has begun.

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1.0 INTRODUCTION

This program effort has two main objectives. The first objective (Contract Line Item A001) is to demonstrate the feasibility of an RF turn-on, RF turn-off, reentrant stream crossed-field amplifier to minimize or eliminate modulation requirements. The second objective of this program (Contract Line Item A002) is to increase the power output capability previously demonstrated (on Contract AF 30(602)-4082) by a factor of two.

This development program is a continuation of ARPA sponsored work begun on Contract AF30(602)-4082. Under that contract, the SFD-237 was developed and operated at a peak power of 1 Mw and an average power of 10 kw. The vehicle incorporated RF turn on,with RF turn off accomplished through the use of a control electrode. The RF turn-off experiments using this vehicle have been started and the feasibility demonstrated. To date, RF turn off has been demonstrated reliably at peak power levels of 700 kw with a net gain of 10 db. Full bandwidth operation at the 300 to 500 kw level has also been observed with reliable RF turn off. Further experiments will be conducted in an attempt to optimize the RF turn-off process.

During the period covered by this report, a circular cold test version of the anode slow wave circuit has been constructed and evaluated. The results of the evaluation indicate that electrically no revisions of the circuit dimensions will be necessary; however, construction flaws have been uncovered and are being corrected. The next anode to be constructed is intended for use in a hot test vehicle. The matching techniques are being evaluated for the high power applications. To date, the match to each port of the slow wave circuit exhibits a return loss of at least 15 db from 4.8 GHz to 6.0 GHz.

2.0 SELF TURN-OFF

In the preceding report* the operation of a dc crossed-field amplifier with control electrode turn off was described. Also mentioned were some of the possible ways of reducing or eliminating the pulsed electrode requirements for self turn-off. During this period, several experiments involving electrode position and geometry were performed. The first two experiments involving electrode position did not give evidence of a reliable self turn-off. The fourth experiment which also involved a variation in electrode position was unsuccessful. The third experiment, which combined position and geometrical variations, gave evidence of the first reliable self turn-off operation.

RF turn on and RF turn off have now been reliably demonstrated in a reentrant stream crossed-field amplifier. The vehicle used in this experiment is a modified SFD-237, specifically, the amplifier designated as J35H. The basic design for this amplifier was evolved under Contract AF30(602)-4082. This amplifier uses a bias electrode to which a simulated dc voltage is applied. Under this condition the amplifier can be operated with a dc voltage applied between anode and cathode while the modulation is achieved solely by the application of the RF drive pulse.

In the present experiments the dc bias for the amplifier is simulated by the use of a voltage pulse applied between the control electrode and cathode, as shown schematically in Figure 1. The bias voltage pulse is made longer than the RF drive pulse and is applied before the RF drive pulse as shown in the figure. The simulation of the dc bias is necessary because of equipment limitations, but it is a completely valid technique for these experiments. Figure 2 is a photograph of an oscilloscope presentation of the RF input pulse (lower trace) and the simulated dc bias (upper and longer trace). Upon application of the dc voltage between the anode and cathode, amplification takes place

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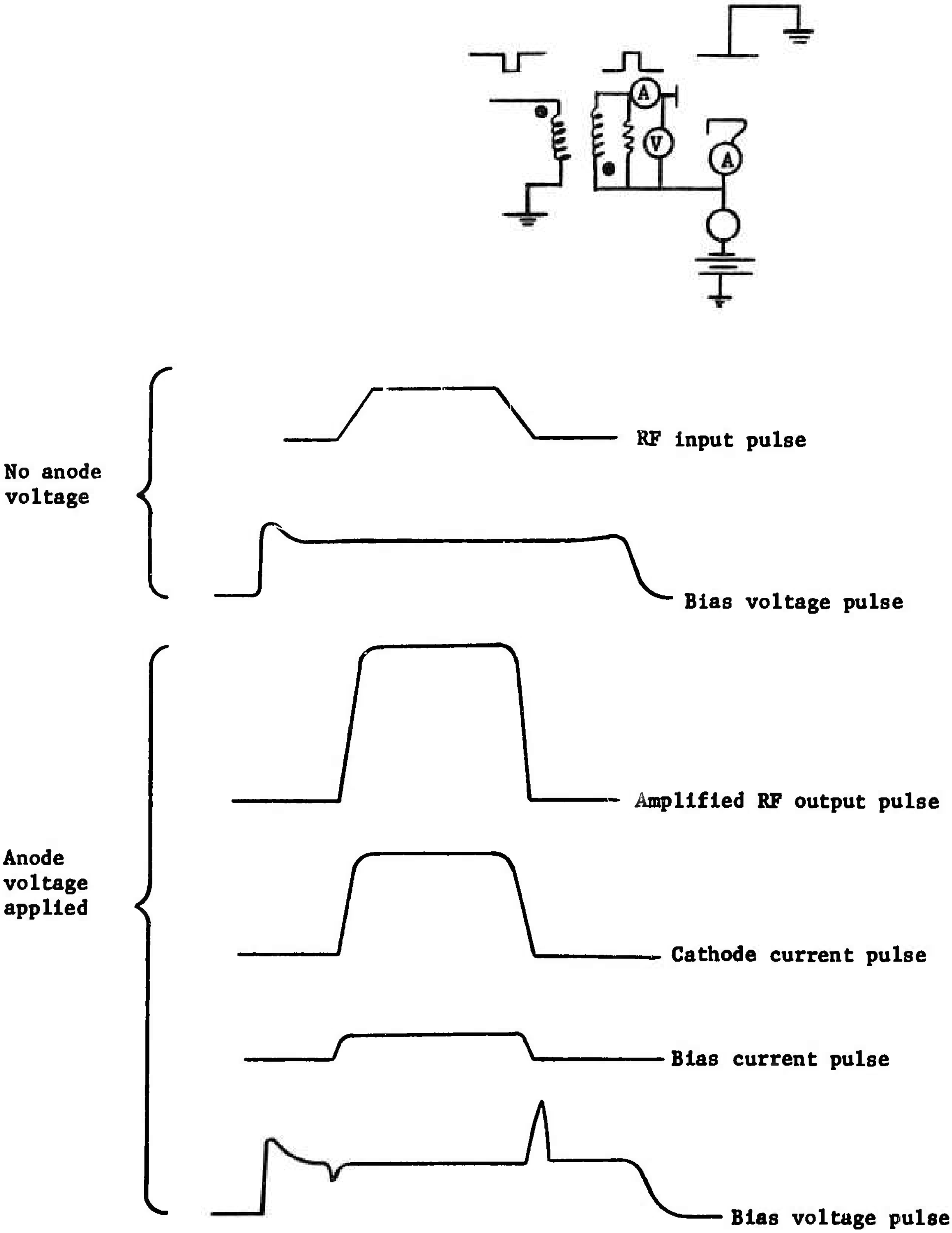

FIGURE 1 PULSING SEQUENCY FOR SIMULATED dc BIAS USED IN SELF-TURN OFF EXPERIMENTS

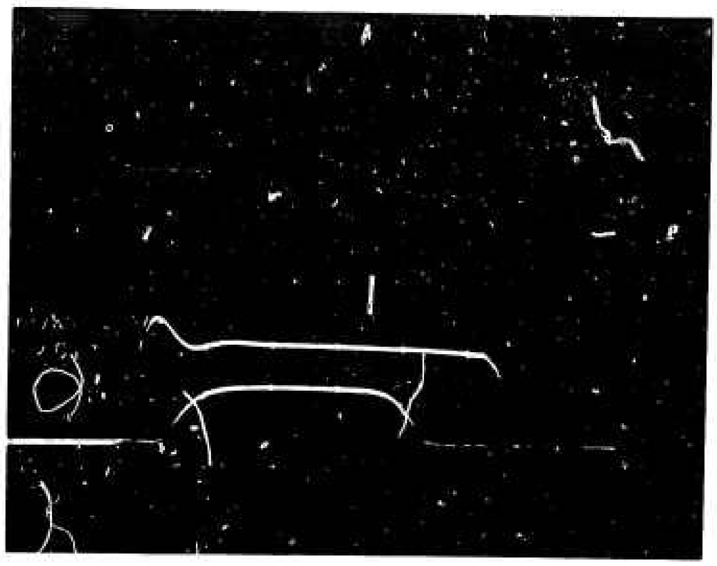

FIGURE 2 BIAS VOLTAGE PULSE (UPPER TRACE) AND RF INPUT PULSE (LOWER TRACE) BEFORE dc SELF-TURN OFF EXPERIMENTS

and we see the presentation shown in Figure 3. The amplified RF output pulse is seen to be the shorter of the two pulses. The bias electrode voltage pulse shape has changed slightly because of the current drawn by the electrode. This current produces a slight loading on the bias modulator during the amplification process. The rapid buildup and decay of current at the beginning and end of the RF pulse cause the ringing effect seen on the voltage pulse. This ringing is due to the inductance in the bias electrode circuit and it is primarily the inductance of the inverting transformer which is used to provide the positive going bias pulse. Figure 4 is a photograph of the bias voltage pulse and bias current pulse. The bias current pulse is shown with the vertical scale expanded by a factor of 4 to bring out the detail. It can be seen that the ringing effects follow the current changes. As further evidence of self turn-off, the amplified RF output envelope and the total cathode current pulse are shown in Figure 5. The RF envelope is seen as the upper trace and the total cathode current pulse is the lower. These data show that the cathode current flow is initiated by the RF input signal and is terminated with the removal of that signal, clearly indicating the complete RF modulation.

Operation of this type has been obtained across the frequency band from 5.4 to 5.9 GHz at power levels from 300 to 500 kw and at several values of constant magnetic fields to insure the reliability of operation. All the tests were conducted at a low duty factor (0.0004) because of equipment limitations. The maximum peak power level which has been observed under the RF modulated conditions and the other performance parameters are shown in Table I. Anode efficiency, η_a, is defined as

$$\eta_a = \frac{p_o}{E_b i_b}$$

where p_o is peak power output
E_b is the dc anode-cathode voltage
i_b is the peak anode current.

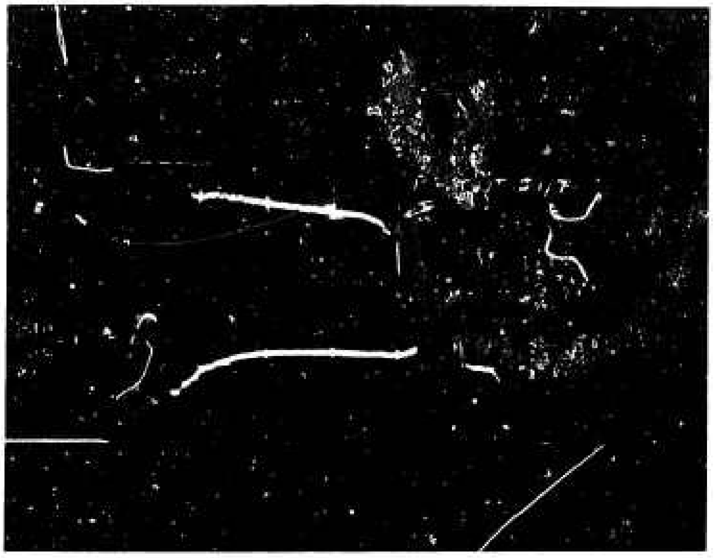

FIGURE 3 BIAS VOLTAGE PULSE (LOWER TRACE) AND AMPLIFIER RF OUTPUT PULSE (UPPER TRACE) INDICATING SELF-TURN OFF

FIGURE 4 BIAS VOLTAGE PULSE (UPPER TRACE), BIAS CURRENT PULSE (MIDDLE TRACE), AND AMPLIFIER RF OUTPUT PULSE (LOWER TRACE) SHOWING SELF-TURN OFF

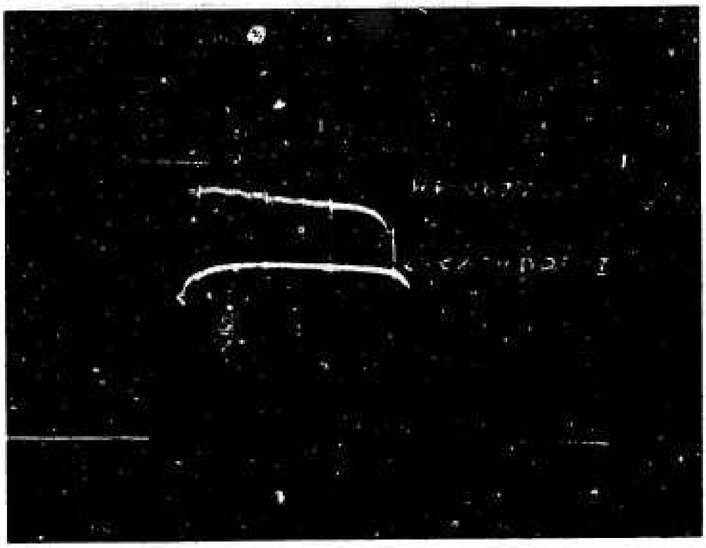

FIGURE 5 CATHODE CURRENT (LOWER TRACE) AND AMPLIFIED RF OUTPUT PULSE (UPPER TRACE) DURING SELF-TURN OFF EXPERIMENTS

TABLE I

PERFORMANCE PARAMETERS
UNDER SELF-MODULATED CONDITIONS

Frequency	5.6 GHz
Pulse length	4 μsec
Duty factor	0.0004
Operating voltage	24.2 kw, dc
Peak cathode current	100 amps
Peak anode current	75 amps
Peak bias current	25 amps
Peak output power	700 kw
Peak input power	67 kw
Net gain	10^+ db
Bias voltage	12.3 kv (simulated dc)
Anode efficiency	38%
Overall efficiency	33%

Overall efficiency, η_{tot}, is defined as

$$\eta_{tot} = \frac{P_o}{E_b i_b + e_{BE} i_{BE}}$$

where e_{BE} is the peak (simulated dc) biased electrode voltage
i_{BE} is the peak biased electrode current

Several aspects of the performance achieved to date are most encouraging. The peak currents were higher than any previously obtained with this vehicle, but more significantly, the high currents were successfully controlled by the biased electrode. The biased electrode operation gives evidence (although it is not conclusive) that noise due to spurious oscillations is markedly reudced, which may lead to increased dynamic range. The most encouraging result is that the efficiency is as high as it is in the first experiments in which complete RF modulation has been reliably demonstrated.

The overall efficiency of operation with the biased electrode appears to be about 85% of the anode efficiency. This decreased efficiency is due to the current being drawn by the bias electrode. The anode efficiency remains the same whether the amplifier is operated with the biased electrode for RF modulation or with the control electrode pulsed after the removal of the RF input signal. It is significant to note that since the anode efficiency is not affected by the presence of the biased electrode, the thermal properties of the anode circuit and the cathode remain unchanged. This indicates that the vehicle should be capable of operating at the high average power previously demonstrated under Contract AF30(602)-4082. The anode dissipation and the cathode back bombardment power are directly dependent upon the anode efficiency and since the anode efficiency is not changed, the dissipations are not changed. The additional current which causes the lower total efficiency flows between the cathode and bias electrode and results in the additional power being dissipated on the bias electrode. This

dissipated power may be removed by passing the coolant through the bias electrode. The most serious effect of the bias current is to have increased the cathode current loading by approximately 30%. Up to this point it appears that the additional cathode loading has not been a problem; however, every effort will be made to reduce the bias current and thereby reduce the loading and raise the overall operating efficiency.

While the anode efficiency of 38% is lower than the 50% value normally observed, it does not appear to be related to the use of a biased electrode. Our observations indicate that quite possibly the reduced efficiency common to both test vehicles is a result of a common change in the vehicles. The one change which was common to both vehicles was an alteration of the drift space geometry which could result in reduced efficiency. The test vehicles will now be opened and examined for evidence of this behavior. It should be stressed that the successful self turn-off is not achieved at the expense of anode efficiency. On the contrary, if anode efficiency can be increased, it will be possible to obtain self turn-off of higher output power for the same level of controlled current.

3.0 HIGH POWER AMPLIFIER (SFD-252)

Based upon the design criteria described in the preceding report, a linear version of the anode slow wave circuit was constructed and tested. Figure 6 is a photograph of the linear version. The preliminary matching technique for the transition from coaxial line to the slow wave circuit was also developed on this tester. The coaxial lines can be seen on both ends of the linear circuit. The results were quite satisfactory and no major revisions were necessary. Based upon these results, a circular version of the anode slow wave circuit was constructed.

3.1 Circular Slow Wave Anode

Since the circular version of the slow wave anode is quite different from those previously used, it was decided that the circular cold test anode should be constructed using the techniques and materials that would be used in a hot test tube. A mechanical evaluation of the anode indicated that the circuit was adequate for cold test studies but was not satisfactory for use in a hot test vehicle. The major difficulty encountered was the poor yield of good brazed joints between the anode bars and the helical coupling elements. The poorly brazed joints obviously could not be tolerated during high power operation when hot spots are likely to destroy the tube. Based upon this observation, the anode circuit was redesigned to incorporate materials which will yield better joints and a structurally stronger anode. The techniques developed for the assembly of the anode worked quite well otherwise and will be used again. The next slow wave anode to be constructed is intended for use in the first hot test vehicle.

3.2 Cold Test - Circular Slow Wave Anode

The circular version of the cold test vehicle has been evaluated, and the results were found to be identical with those obtained with the linear version. The dispersion curves for both the linear and circular versions were identical and are shown compared to

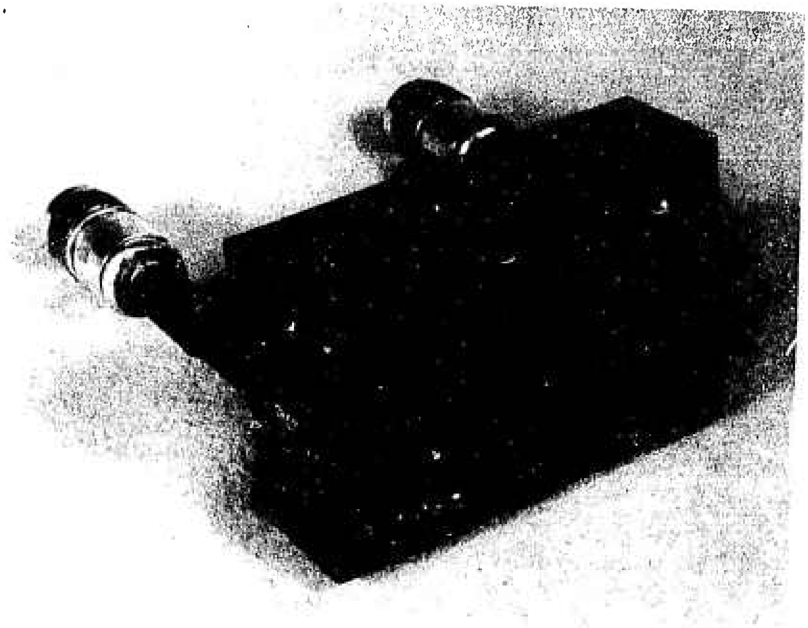

FIGURE 6 LINEAR VERSION OF SLOW WAVE ANODE CIRCUIT

the calculated curve in Figure 7. The interaction impedance and field distribution also appear to be quite similar, therefore construction of the first hot test anode has been started.

Since the anode circuit properties seemed to be well under control, the next step was to incorporate the matching transitions using the technique developed with the linear version. The match obtained with the linear version was accomplished using small coaxial lines to accommodate the existing test equipment. The technique for launching the energy onto the slow wave circuit was valid, but the physical size of the coaxial lines would not be adequate for the anticipated power levels in a hot tube. In order to incorporate the matching transitions to be used in a hot tube, a broad band waveguide to coaxial transition had to be designed using components capable of handling the high average and peak powers anticipated. The method used for this transition is a capacitive post design which is capable of being water cooled to insure safe operation at the high power levels. The match obtained with the waveguide to coaxial transition is shown in Figure 8. The mismatch loss is less than 0.1 db across the required band.

Using the waveguide to coaxial transition and the technique for launching the energy onto the slow wave circuit, we proceeded to optimize the overall match to the cold test vehicle. Figure 9 shows a photograph of the circular cold test assembly and the waveguide input and output arms. In the photograph the waveguides are parallel and extend in the same direction; this was done to facilitate testing. Since the transition from waveguide to the slow wave circuit is coaxial, either waveguide may be oriented in any position around 360° in the plane of rotation. In the hot tube the waveguides will be attached for "in line" operation; that is, the waveguides will be parallel but 180 degrees apart and separated by approximately the tube body diameter.

The overall match obtained with the transitions described is shown in Figure 10. The return loss from the illuminated port is seen to be at least 15 db over the range from approximately 4.8 GHz to

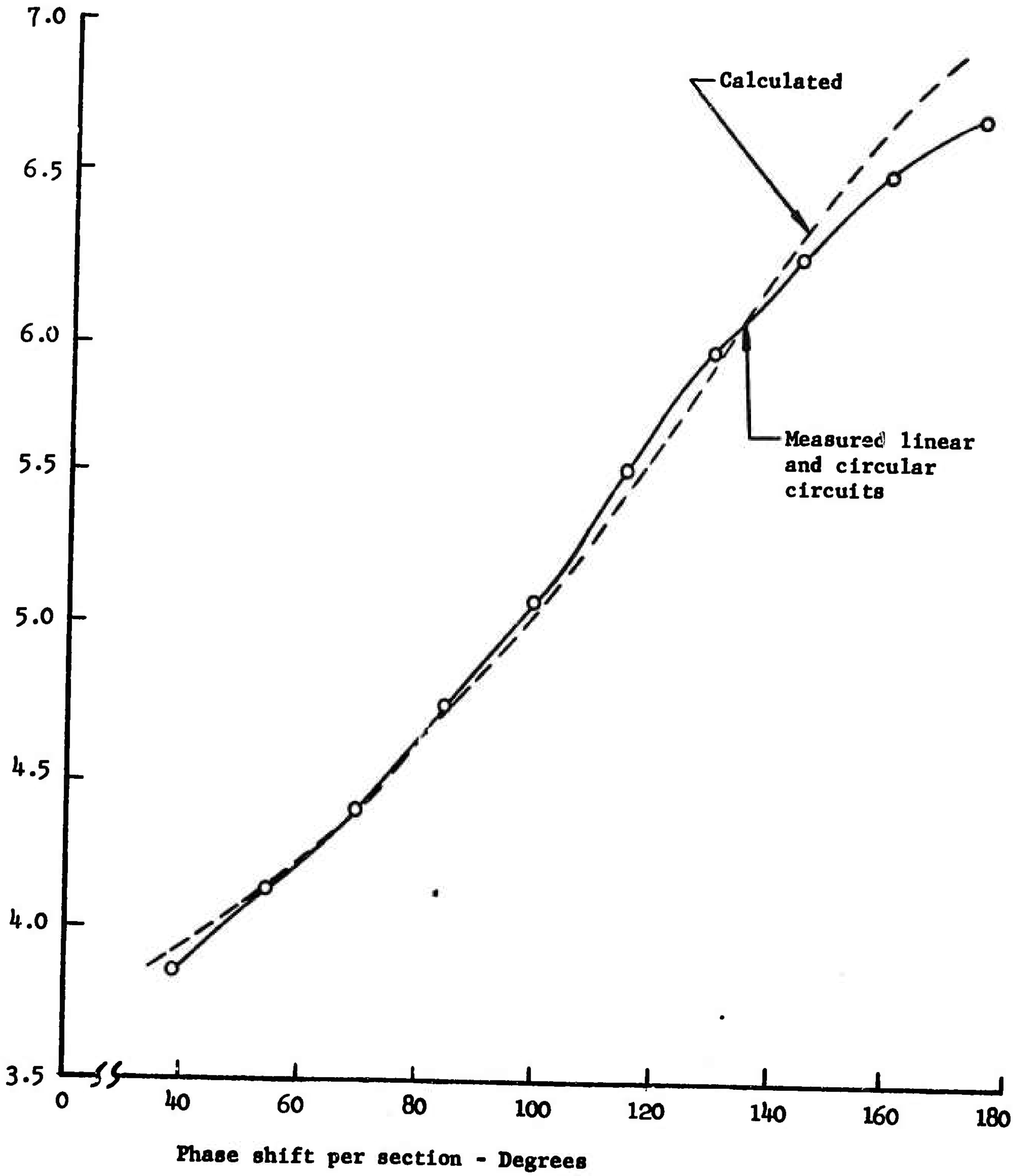

FIGURE 7 DISPERSION CURVES FOR LINEAR AND CIRCULAR SLOW WAVE CIRCUITS

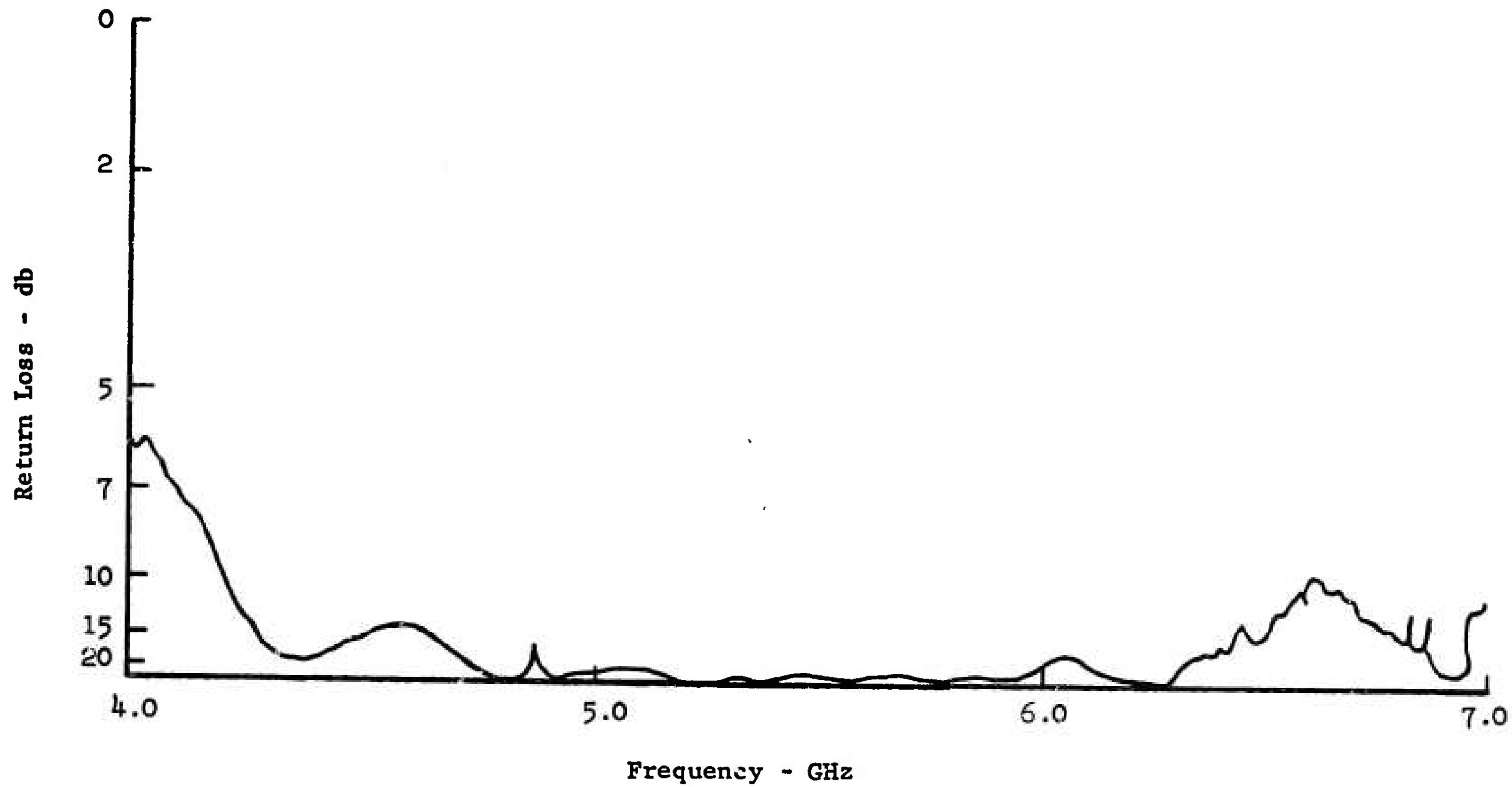

FIGURE 8 WAVEGUIDE TO COAXIAL TRANSFORMER RETURN LOSS - CAPACITIVE POST DESIGN

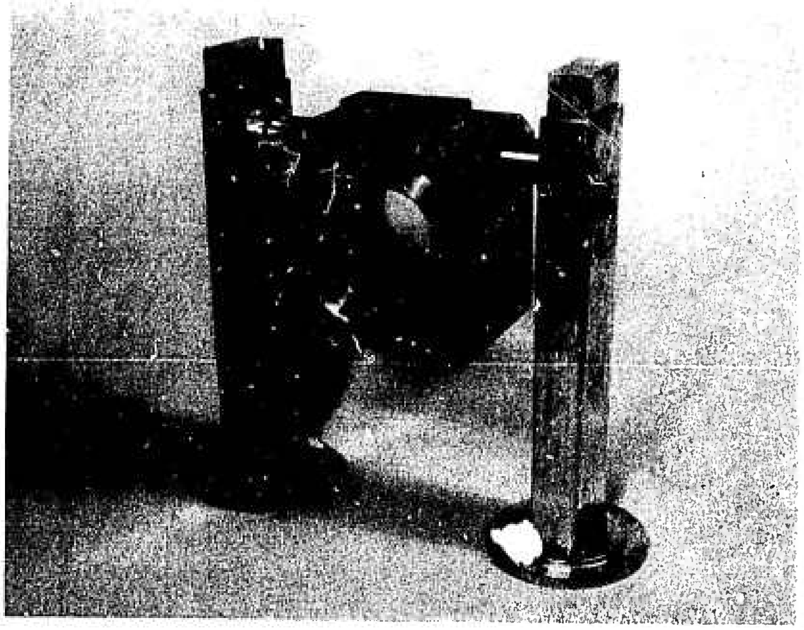

FIGURE 9 CIRCULAR COLD TEST ASSEMBLY WITH WAVEGUIDE INPUT AND OUTPUT ARMS

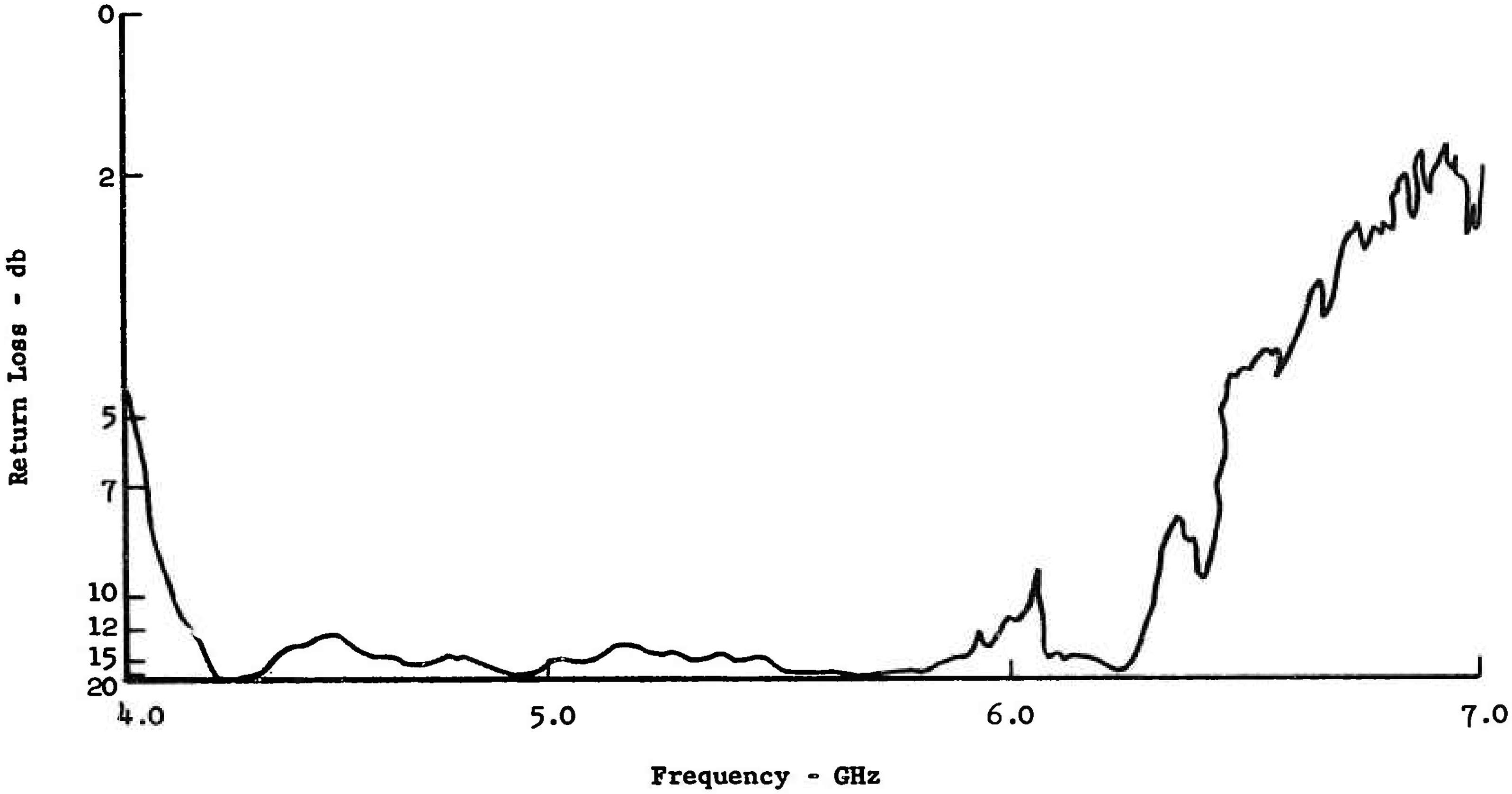

FIGURE 10 RETURN LOSS OF INPUT TRANSITION

6.0 GHz. The insertion loss appears to be approximately 3 to 4 db across the operating band of 5.425 GHz to 5.925 GHz. Although this preliminary match appears to be adequate for the first hot test vehicle, it is not considered to be optimized so that the effort to improve the match will be continued. One critical test must still be performed before the match can be used in the first hot test vehicle. When a simulated cathode is introduced into the cold tester, there must be no significant degradation of the match or insertion loss. Past experience has shown that when the slow wave circuit is properly matched, the presence of the cathode makes little or no difference. However, the cathode may cause an end space resonance to appear in the operating band and if indeed a resonance does occur, it must be shifted out of the band where it can do no harm.

3.3 Construction of the Hot Test Vehicle

The overall tube layout has been completed and detailed so that construction of the hot test vehicle is in progress. All parts for the slow wave anode circuit are nearly complete and assembly of the anode should be completed before the end of February 1968. All long lead time items have been placed on order, and it is expected that the first hot test vehicle will be completed by the first week of April 1968.

3.4 Magnetic Circuit

The magnetic field uniformity produced by the pole piece geometry has been evaluated with electrolytic tank field plots and appears to be satisfactory. The parts for the magnetic cold tester have now been completed and will be evaluated to confirm the electrolytic tank plots. If any corrections are found to be necessary, they will be of a minor nature and should not affect the delivery of the first vehicle for hot test.

4.0 PROGRAM FOR NEXT PERIOD

1. Continue with attempts to improve match on circular cold tester.
2. Continue and complete construction of first hot test vehicle.
3. Continue tests to evaluate and optimize the control electrode self turn-off.
4. Evaluate magnetic cold tester circuit for field uniformity.

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